Tutorial lecture on Modeling and simulation of high-speed interconnects: approaches, challenges, and solutions

Modeling and Simulation of High-Speed Interconnects: Approaches, Challenges and Solutions

Stefano Grivet Talocia, Piero Triverio

Dept. Electronics, Politecnico di Torino
stefano.grivet@polito.it
piero.triverio@polito.it

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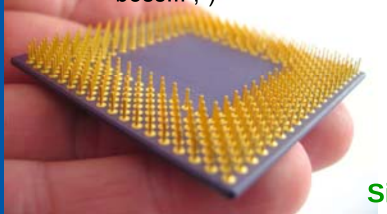
Complexity of electronic interconnects

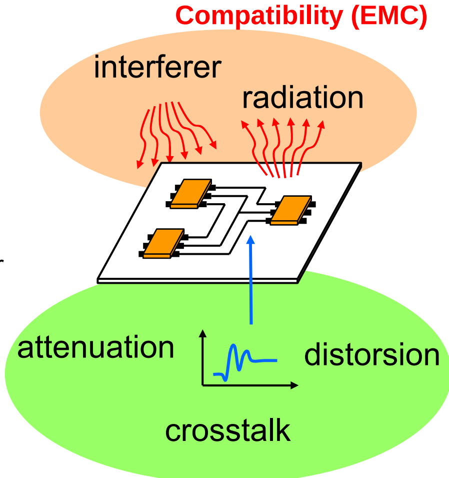
Computer aided design techniques are essential for interconnects design.

Strong impact on:

- performance & reliability
- product time-to-market
- company revenues
- ... and so the relations with your boss... ;-)



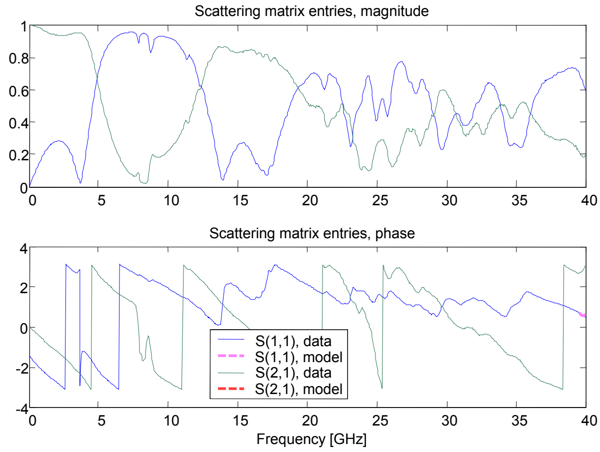
Electromagnetic Compatibility (EMC)



Signal Integrity (SI)

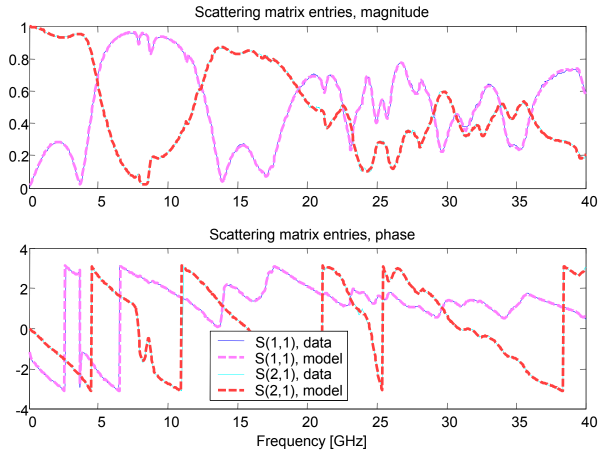
A successful example... (stripline with launches)

Data: measured S-parameters



A successful example... (stripline with launches)

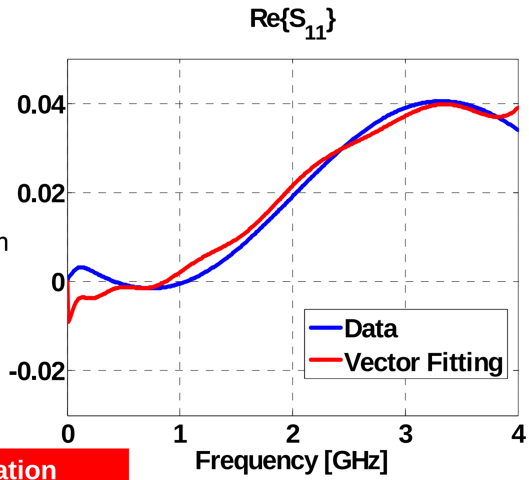
Macromodel: 60 poles



An example of failure... (courtesy of Nokia)

Three coupled lines

Scattering parameters from an electromagnetic simulation



Macromodel generation dramatically fails! But why? Where is the problem?

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Computer Aided Design: always hassle-free?

Problems are not uncommon!

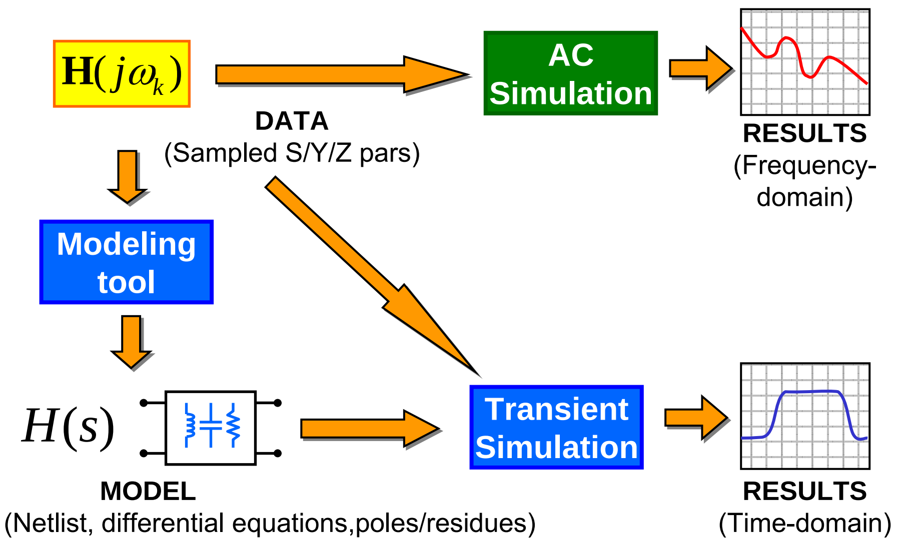
Examples:

- Simulator errors and warnings (“Convergence failure”, “Timestep too small”, “Malformed impulse response”,...)
- Data fitting problems
- Inaccurate simulation results

Such issues may strongly impair the design workflow!

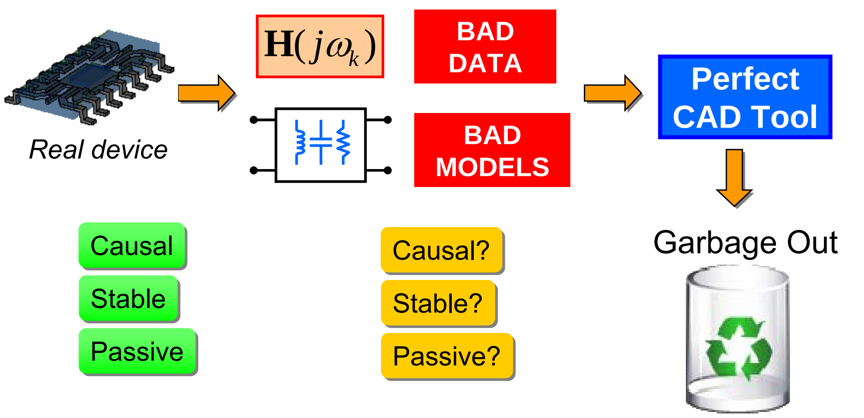
- Increase product time-to-market
- Post-sale malfunctioning
- Trade performance for reliability

Reference scenario: interconnects simulation



Poor physical consistency is the cause!

A primary cause of these problems is a lack of physical consistency:



Our goal

UNDERSTAND
What do these terms mean!

HOW
Violations can arise

ISSUES
How badly they can ruin my design

BEST PRACTICES
Rules to defeat them

Benefits

Actually, **let us make them work for us**, to improve our design workflow!

- Measurement step
  - Promptly detect inconsistencies & fix the measurement
  - ... before wasting hours/days in trying to get the design done!
- Modeling step
  - prevent modeling failures
  - maximize accuracy
- Simulation step
  - more accurate results
  - avoid convergence issues

Agenda

- **Causality & stability of models**
- Causality & stability of frequency data

- Passivity of models
- Passivity of frequency data

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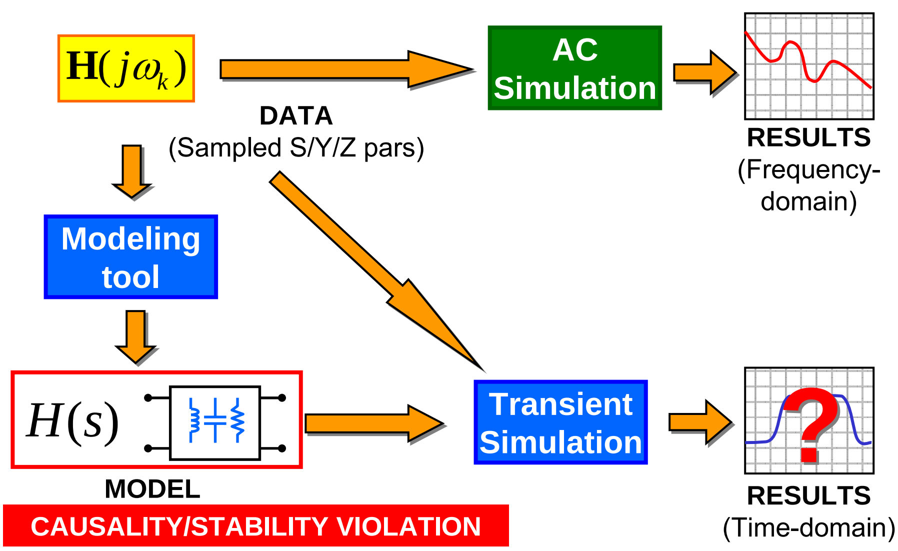
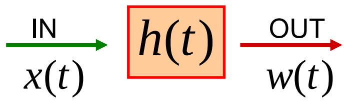
Causality/stability violation in a MODEL



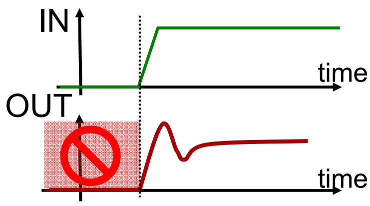
Causality: definition

- We consider a linear system (single input single output)

$$w(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau$$



- Causality: "no output before the input"
- No anticipatory behavior
- All physical (real) systems are causal! (active, passive, nonlinear,...)



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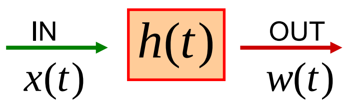
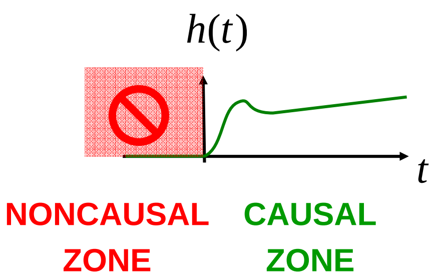


- Causal system:

$$\boxed{h(t) = 0 \quad t < 0}$$



Stability: definition

- BIBO Stability: "if any Bounded Input leads to a Bounded Output"

$$w(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau \qquad \xrightarrow[x(t)]{\text{IN}} \boxed{h(t)} \xrightarrow[w(t)]{\text{OUT}}$$

- Stability condition:

$$\boxed{\int_{-\infty}^{+\infty} |h(t)|dt < \infty}$$

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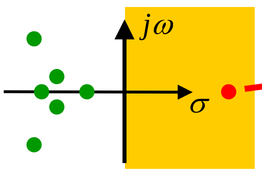
Causality and stability in Laplace domain

- We apply the Laplace transform

$$w(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau \xrightarrow{L} W(s) = H(s)X(s)$$

- Causality & stability condition (for lumped systems): *if all poles of $H(s)$ lie in the left hand plane $Re\{s\}<0$, then the system is stable and causal*



Causality/stability violated!

Causality/stability violations in MODELS

HOW can causality/stability violations arise?

- Causality/stability not enforced by modeling algorithm
- Noisy data
- Model order too large (estimation of redundant poles ill-conditioned)

- What happens when a model is not causal/stable?

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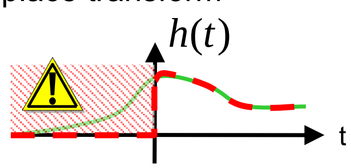
Causality/stability violations in MODELS: issues

Many commonly used theoretical results may be inappropriate! Example: Laplace transform

$$H(s) = \int_0^{+\infty} h(t) e^{-st} dt$$



- The commonly used **one-sided** Laplace transform is not appropriate for possibly non-causal systems!
- Two-sided Laplace transform must be used!

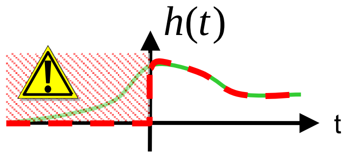
$$H(s) = \int_{\boxed{-\infty}}^{+\infty} h(t) e^{-st} dt$$

- More complicated.... here avoided!

Causality/stability violations in MODELS: issues

Another example: which convolution formula?

$$w(t) = \int_{\boxed{0}}^{\boxed{t}} h(\tau)x(t-\tau)d\tau$$



- OK only for causal systems! Otherwise integration must be performed from -∞ to +∞

Time-domain circuit simulators based on the convolution formula may not support noncausal models!

Causality/stability violations in MODELS: issues

We consider those simulators that directly integrate the circuit differential equations:

$$\boxed{H(s)} \Rightarrow \boxed{\dot{\mathbf{y}}(t) = \mathbf{A}\mathbf{y}(t) + \mathbf{B}x(t)}$$

$$\mathbf{y}(0) = ?$$

Initial condition

Causality/stability violations in MODELS: issues

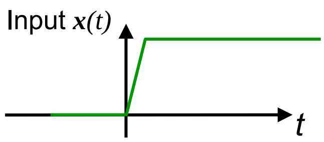
We consider those simulators that directly integrate the circuit differential equations:

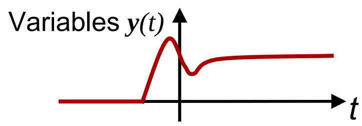
$$\boxed{H(s)} \Rightarrow \boxed{\dot{\mathbf{y}}(t) = \mathbf{A}\mathbf{y}(t) + \mathbf{B}x(t)}$$

$$\mathbf{y}(0) = 0$$

Initial condition

Wrong for non-causal models!!





Time-domain simulators based on integration of differential equations do not support noncausal models!

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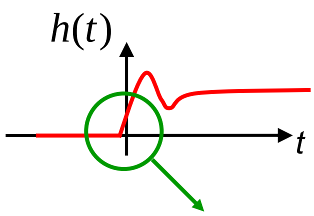
Causality/stability violations in MODELS: issues

Since all physical systems are causal, a non-causal model is for sure an approximation of the original system

$$\boxed{H(s)} \Rightarrow$$

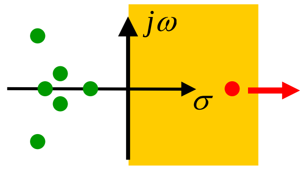


Maybe a good approximation (small causality violation), but...

Causality/stability violations in MODELS: issues

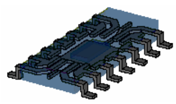
Small causality violations can lead to large problems and inconsistencies!

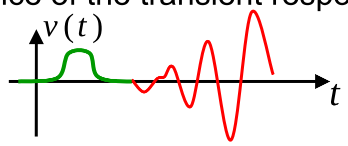
$H(s)$



Noncausal/unstable pole with very small residue

- Negligible effect on the model transfer function $H(s)$
- But **dramatic** influence of the transient response!





UNSTABLE BEHAVIOR!

Best practices

Bottom line: Noncausal/unstable models can lead to serious problems!

- Always enforce stability and causality during model construction (with any method):
  - Vector Fitting **OK**
  - Many order reduction methods **OK**
- Safer than enforcing causality during circuit simulation

$H(s)$

Causal Results

NOT CAUSAL

The original model must somehow be modified...

Best practices

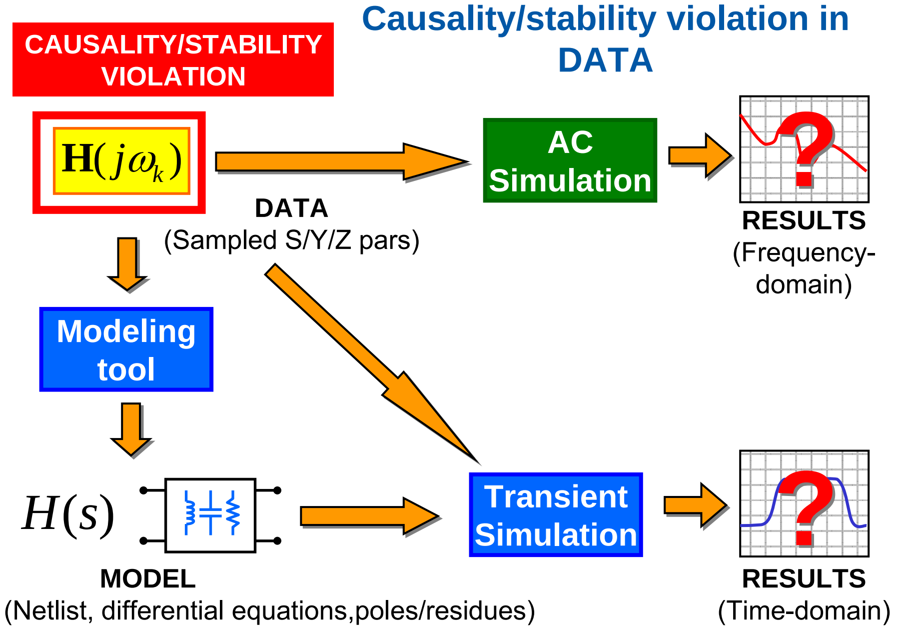
Bottom line: Noncausal/unstable models can lead to serious problems!

- Always enforce stability and causality during model construction (with any method):
  - Vector Fitting **OK**
  - Many order reduction methods **OK**
- Safer than enforcing causality during circuit simulation

SAFE WAY $H(s)$ **CAUSAL** → → Causal Results

No loss of accuracy!

Causality/stability violation in DATA



Causality in frequency domain

- We apply the Fourier transform

$$w(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau \xrightarrow{F} W(j\omega) = H(j\omega)X(j\omega)$$

- This is mathematically correct only for **stable** systems
- Causality condition: the frequency response must satisfy the **Kramers-Krönig dispersion relations** (Hilbert transform)

$$H(j\omega) = U(\omega) + jV(\omega)$$

$$\boxed{\begin{cases} U(\omega) = \dfrac{1}{\pi}\, pv \displaystyle\int_{-\infty}^{+\infty} V(\omega')\frac{d\omega'}{\omega-\omega'} \\ V(\omega) = -\dfrac{1}{\pi}\, pv \displaystyle\int_{-\infty}^{+\infty} U(\omega')\frac{d\omega'}{\omega-\omega'} \end{cases}}$$

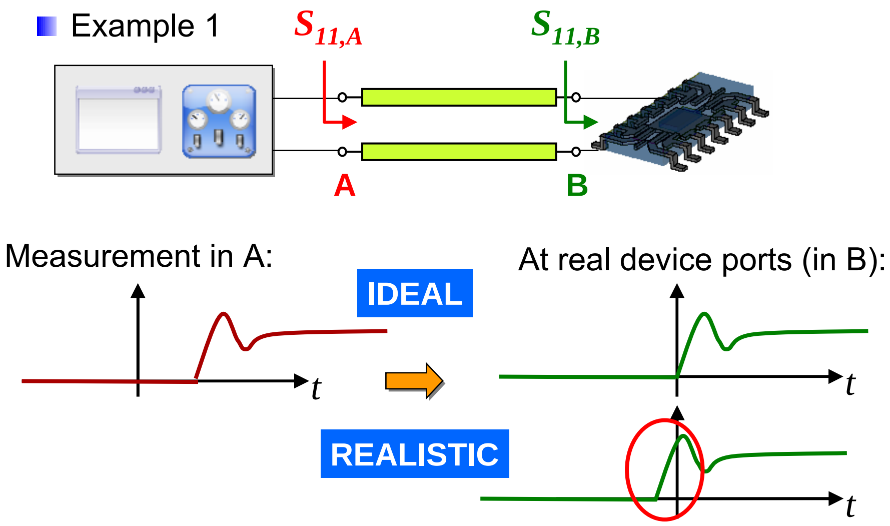
Causality violations in FREQUENCY DATA

HOW can causality violations arise?

- Numerical simulation: poor meshing, bad models or assumptions on material properties, inaccurate solver, human mistakes
- Measurement: Improper VNA calibration/de-embedding, human mistake, noise

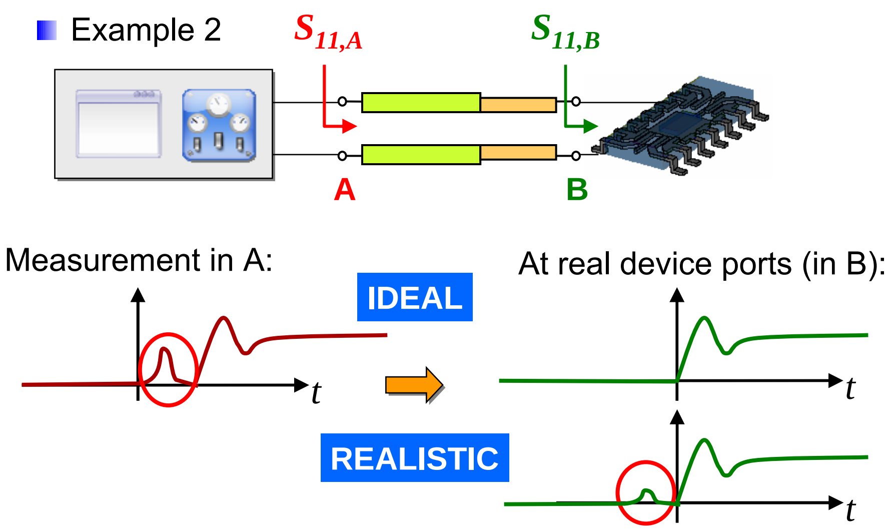
Improper VNA calibration leading to causality violations

- Example 1



Improper VNA calibration leading to causality violations

- Example 2



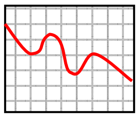
CAUSALITY/STABILITY VIOLATION

Causality/stability violation in DATA

$\mathbf{H}(j\omega_k)$

DATA
(Sampled S/Y/Z pars)

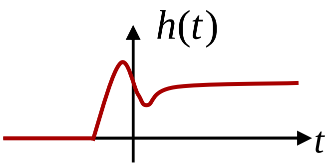
AC Simulation



RESULTS
(Frequency-domain)

Non-physical (non-causal) results

If transformed to the time-domain:



CAUSALITY/STABILITY VIOLATION

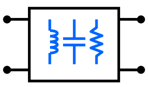
Causality/stability violation in DATA

$\mathbf{H}(j\omega_k)$

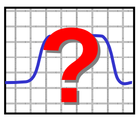
DATA
(Sampled S/Y/Z pars)

Modeling tool

$H(s)$



Transient Simulation



MODEL
(Netlist, differential equations,poles/residues)

RESULTS
(Time-domain)

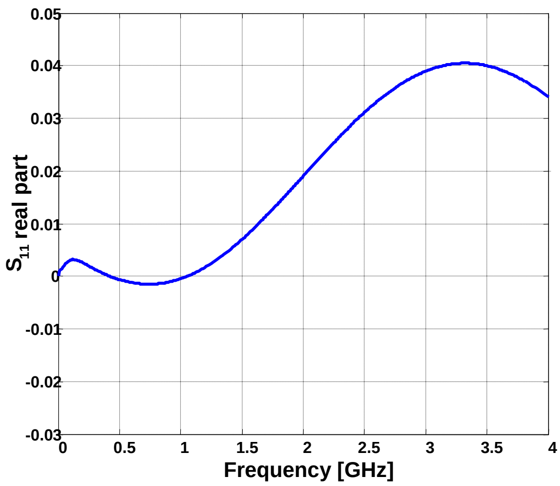
Example (courtesy of Nokia)

Three coupled lines

EM simulation

$\mathbf{H}(j\omega_k)$

NON-CAUSAL



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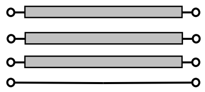
Three coupled lines



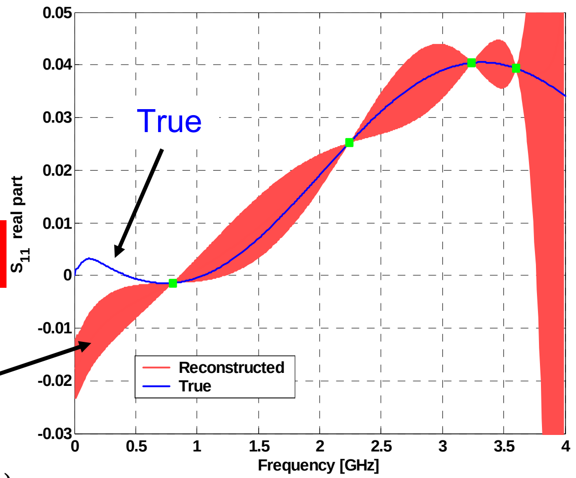
EM simulation

$\mathbf{H}(j\omega_k)$

NON-CAUSAL

Computed with dispersion relations

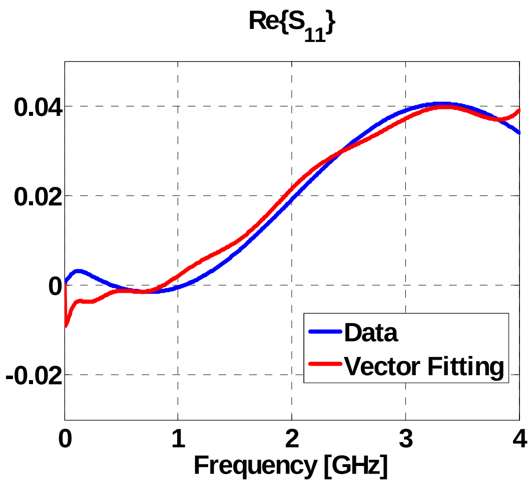
$$H(j\omega) = U(\omega) + jV(\omega)$$



Example (courtesy of Nokia)

Three coupled lines

Vector fitting fails... because of causality violations!



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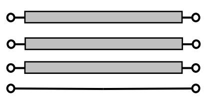
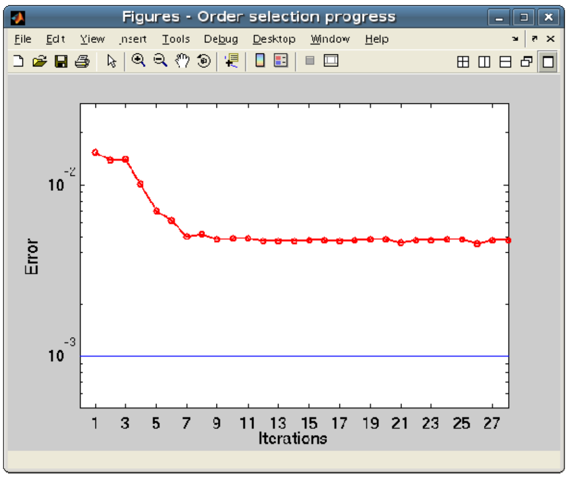
Example (courtesy of Nokia)

Three coupled lines



Vector fitting fails... because of causality violations!

Even if the number of poles is increased up to 50, error does not decrease!



Courtesy of IdemWorks s.r.l.

Example (courtesy of Nokia)

Three coupled lines

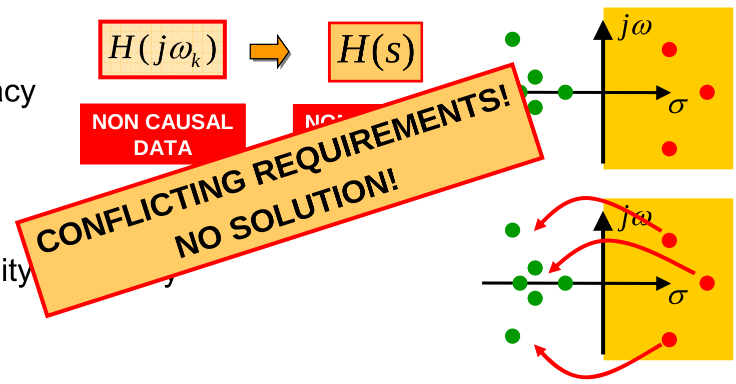
Vector fitting fails... because of causality violations!

```
Building model New using FDVF
Performing FDVF Model Generation ...
Iteration 1
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
  RMS Error: 0.00498987   Max Dev: 0.0122055

.... [snip] ....

Iteration 15
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
  RMS Error: 0.00385667   Max Dev: 0.0100463
```


Explanation of Vector Fitting difficulties

Vector fitting is required to fulfill two requirements:

- Accuracy
- Causality



Causality/stability violation in DATA

CAUSALITY/STABILITY VIOLATION

$\mathbf{H}(j\omega_k)$

DATA
(Sampled S/Y/Z pars)

Modeling tool

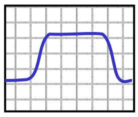
Stability/causality is enforced

INACCURATE!

MODEL
(Netlist, differential equations,poles/residues)

Transient Simulation

Inaccurate results!



RESULTS
(Time-domain)

Causality/stability violation in DATA

CAUSALITY/STABILITY VIOLATION

$\mathbf{H}(j\omega_k)$

DATA
(Sampled S/Y/Z pars)

Modeling tool

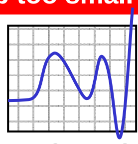
Stability/causality NOT enforced

NOT STABLE&CAUSAL!

MODEL
(Netlist, differential equations,poles/residues)

Transient Simulation

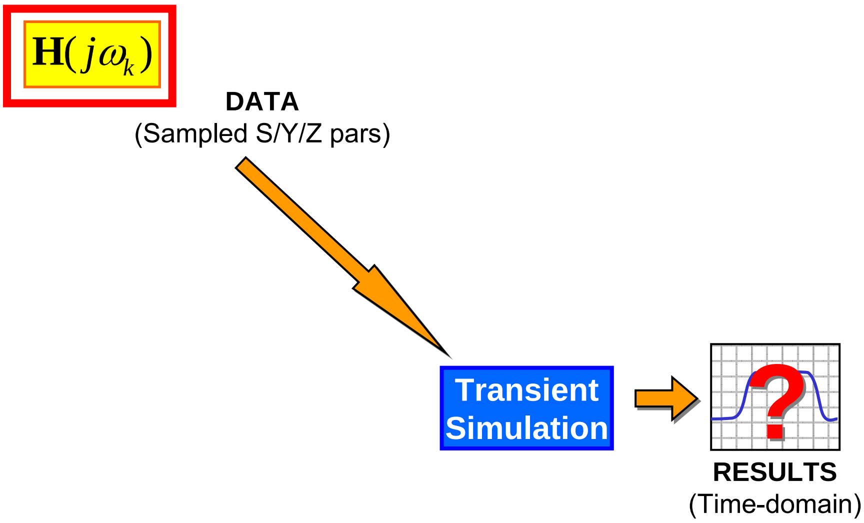
Divergent results “Timestep too small”



RESULTS
(Time-domain)

CAUSALITY/STABILITY VIOLATION

Causality/stability violation in DATA

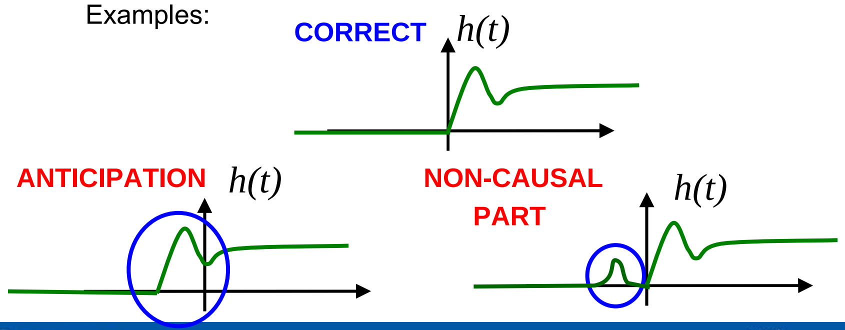


Causality/stability violation in DATA

The simulator must convert the frequency data to the time-domain. It will either:

- fit a macromodel→ convergence or accuracy issues
- find the impulse response $h(t)$ and then do convolution → the impulse response will be non-causal

Examples:



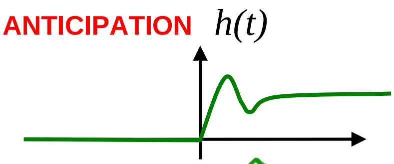
Dealing with a non-causal impulse response

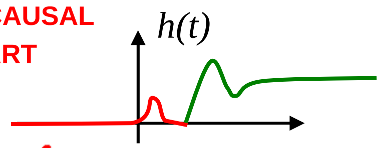
The simulator may:

- do nothing → non-causal waveforms

Will you trust your results?
(may be critical for timing analysis)

- try to compensate the violation introducing a delay





Accuracy/timings loss

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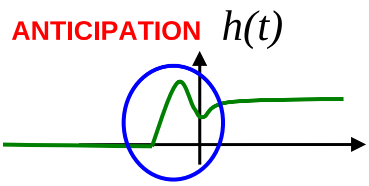
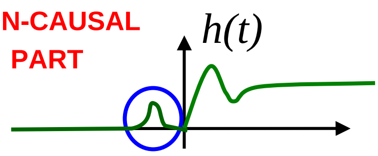
Dealing with a non-causal impulse response

The simulator may:

- eliminate the non-causal part





Accuracy loss

Hard to devise a causality-correction method that works well in all cases!

Causal frequency data → avoid any problem!

Causality/stability violation in DATA: conclusion

- Frequency data with causality/stability violations lead to a DEAD END!
- Simulation stability or accuracy is compromised!

Best practices

- Check your frequency data for causality violations
- Robust, fully-automated algorithms exist! See [1]

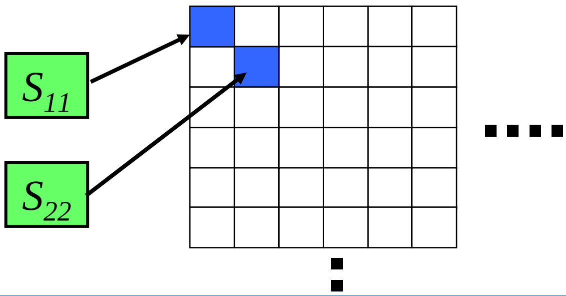
- Reject “bad” datasets and avoid wasting hours trying to get “good” results from them!
- Opportunity to improve your measurement or full-wave simulation process!

[1] P. Triverio and S. Grivet-Talocia, “Robust Causality Characterization via Generalized Dispersion Relations", IEEE Transactions on Advanced Packaging, vol. 31, n.3, 2008

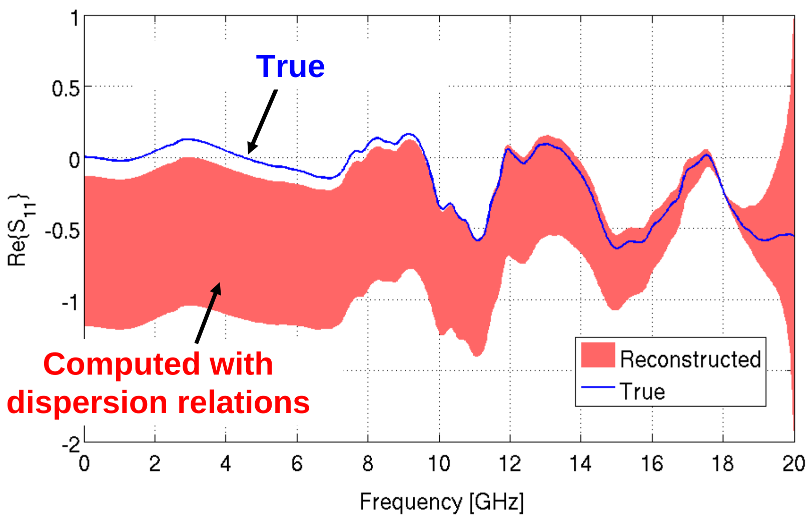
Another example: high-speed connector (courtesy of IBM)

- High performance connector
- Nine signal lines (18 ports)
- Scattering parameters computed with a field solver

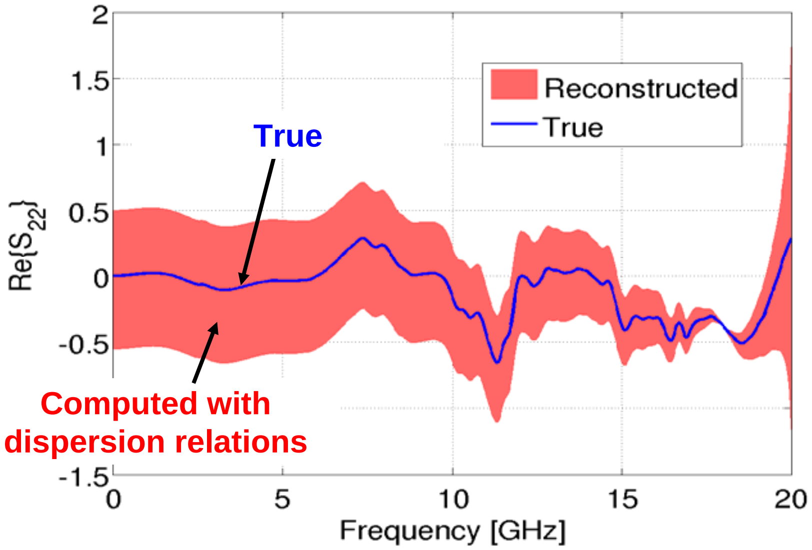
Scattering matrix



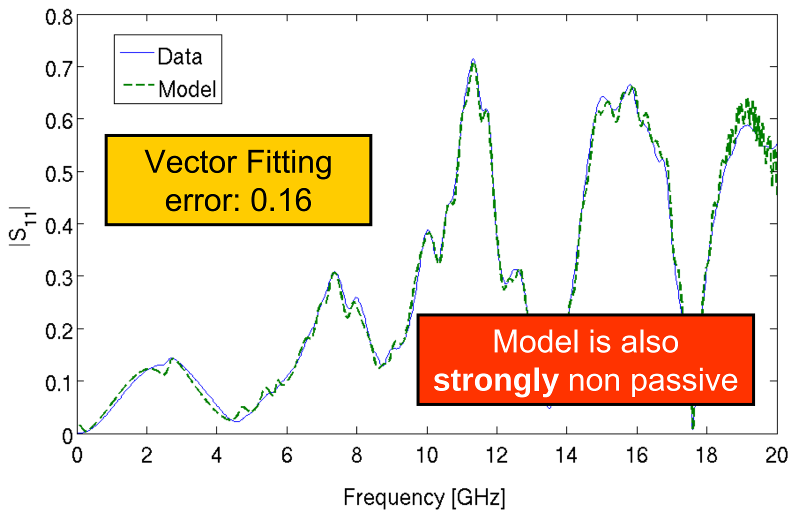
S_{11} is not causal!



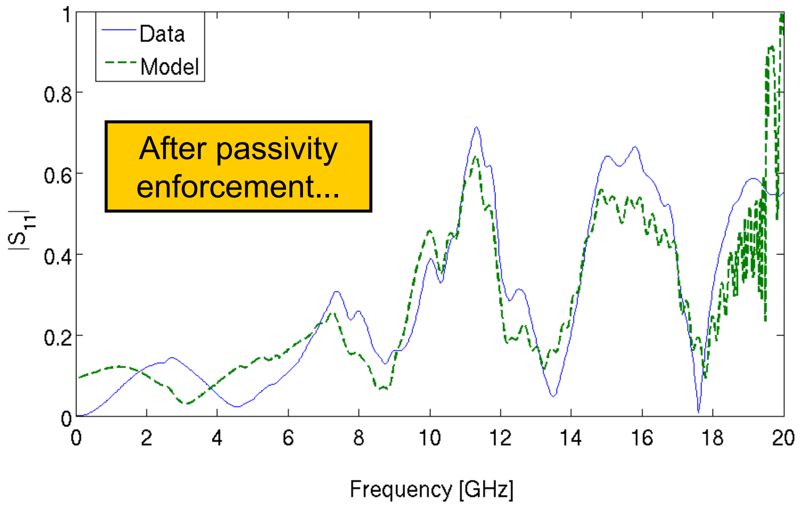
S_{22} is instead consistent



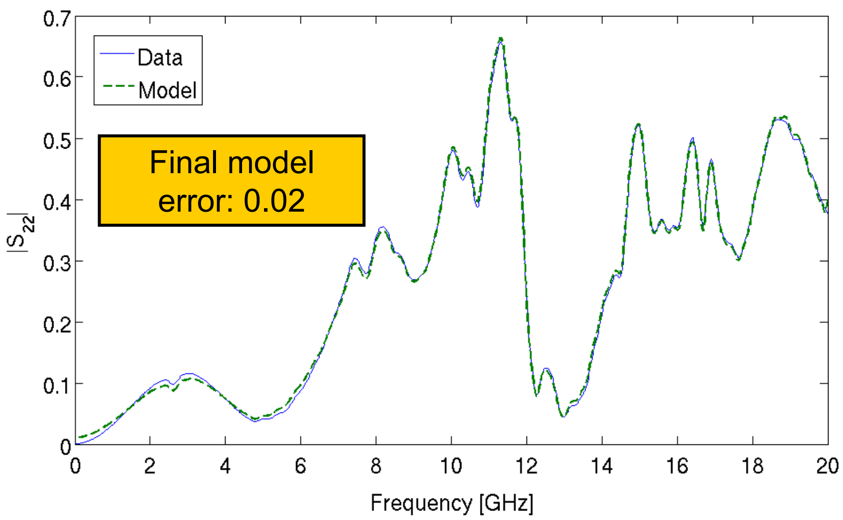
S_{11} modeling is problematic...



S_{11} modeling is very problematic!

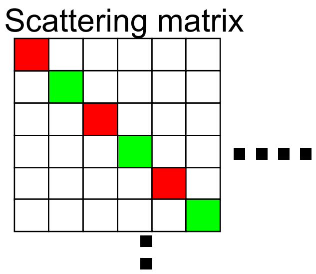


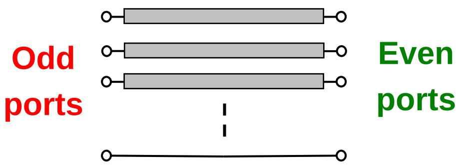
S_{22} modeling instead ends successfully!



Causality violations pattern

- S_{11} S_{33} S_{55},... violate causality
- S_{22} S_{44} S_{66},... are instead OK

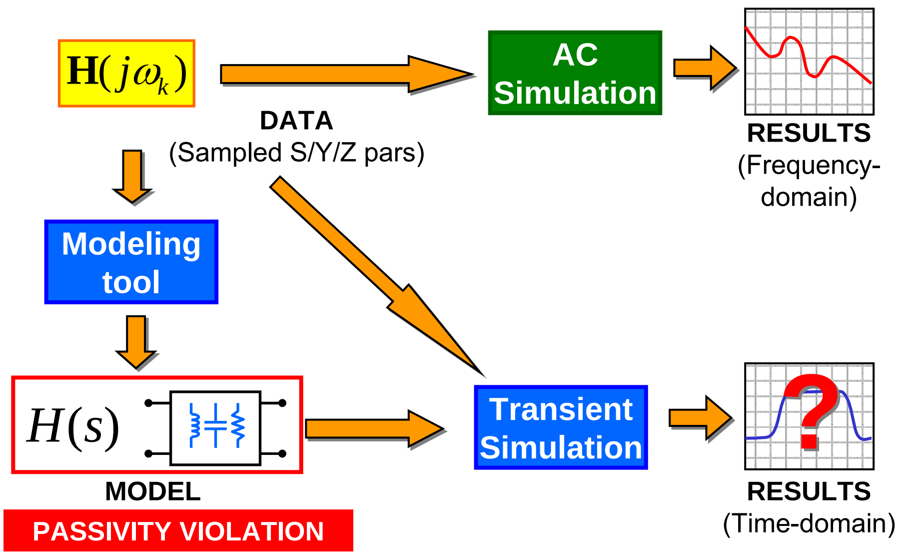




- Something got wrong in the de-embedding of odd numbered ports
- Useful information to correct the S-parameters computation!

S.Grivet-Talocia and P.Triverio, SPI2010 Tutorial lecture, 9 May 2010, Hildesheim, Germany

Passivity violation in a MODEL



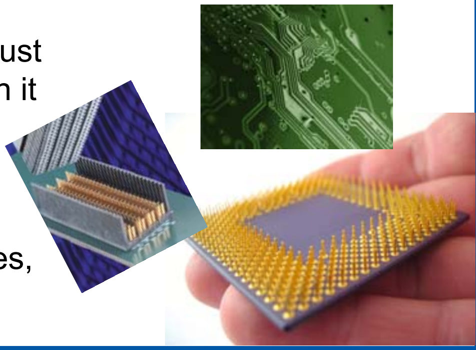
Passivity: definition

- We consider a linear system (with N ports)

$$\mathbf{w}(t) = \int_{-\infty}^{+\infty} \mathbf{h}(\tau)\mathbf{x}(t-\tau)d\tau \qquad \xrightarrow[\mathbf{x}(t)]{\text{IN}} \boxed{\mathbf{h}(t)} \xrightarrow[\mathbf{w}(t)]{\text{OUT}}$$

- Passivity: "the system must absorb more energy than it generates"

- True for all interconnect elements (packages, lines, connectors,...)



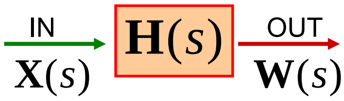
Passivity conditions for transfer functions

$$\xrightarrow[\mathbf{X}(s)]{\text{IN}} \boxed{\mathbf{H}(s)} \xrightarrow[\mathbf{W}(s)]{\text{OUT}}$$

- Scattering representation (similar conclusions for Z/Y)
- Theorem: $\mathbf{H}(s)$ must be bounded real, that is:

1. $\mathbf{H}(s^*)=\mathbf{H}^*(s)$ *To ensure a real-valued* ***h****(t)*

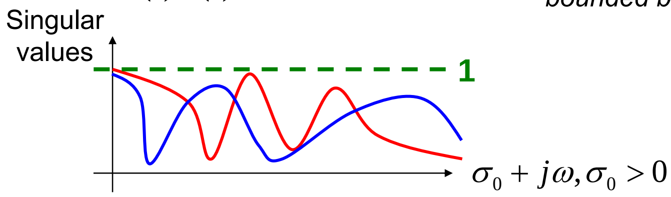
Passivity conditions for transfer functions



- Scattering representation (similar conclusions for Z/Y)
- Theorem: $\mathbf{H}(s)$ must be bounded real, that is:

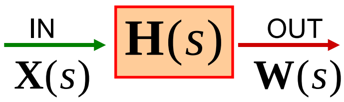
1. $\mathbf{H}(s^*) = \mathbf{H}^*(s)$
2. $\mathbf{H}^H(s)\mathbf{H}(s) \leq \mathbf{I}$ in $Re\{s\} > 0$

Singular values of S matrix bounded by 1 in $Re\{s\}>0$



S.Grivet-Talocia and P.Triverio, SPI2010 Tutorial lecture, 9 May 2010, Hildesheim, Germany

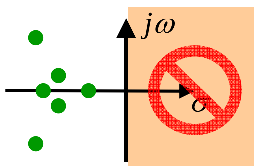
Passivity conditions for transfer functions



- Scattering representation (similar conclusions for Z/Y)
- Theorem: $\mathbf{H}(s)$ must be bounded real, that is:

1. $\mathbf{H}(s^*) = \mathbf{H}^*(s)$
2. $\mathbf{H}^H(s)\mathbf{H}(s) \leq \mathbf{I}$ in $Re\{s\} > 0$
3. each element of $\mathbf{H}(s)$ be analytic in $Re\{s\} > 0$

For lumped systems, no poles in right half plane



Relation to stability and causality

Passivity

Stability **Causality**

Relation to stability and causality

Stability and causality are prerequisites for passivity!

Passivity

Stability **Causality**

Relation to stability and causality

Passivity

Passivity includes all physical consistency requirements

* and the system has no poles on the imaginary axis

*

Stability

Causality

Triverio, Grivet-Talocia, Nakhla, Canavero, Achar, “Stability, causality, and passivity in electrical interconnect models,” *IEEE Trans. on Adv. Pack.*, vol. 30, n. 4, Nov. 2007.

S.Grivet-Talocia and P.Triverio, SPI2010 Tutorial lecture, 9 May 2010, Hildesheim, Germany

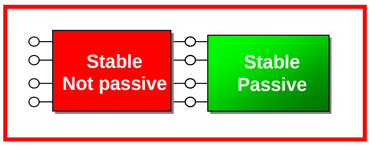
Application: passivity violations in MODELS

HOW can passivity violations arise?

- Passivity not enforced by modeling algorithm
- Approximation errors
- Common problem, especially for components with low losses (e.g. short interconnects, integrated inductors/capacitors,...)

- What happens if a model is not passive??

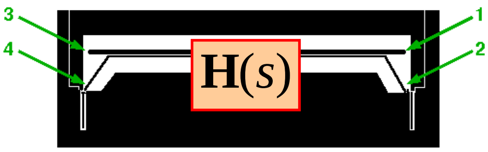
Passivity violations in MODELS: issues



Neither passivity nor stability are guaranteed!

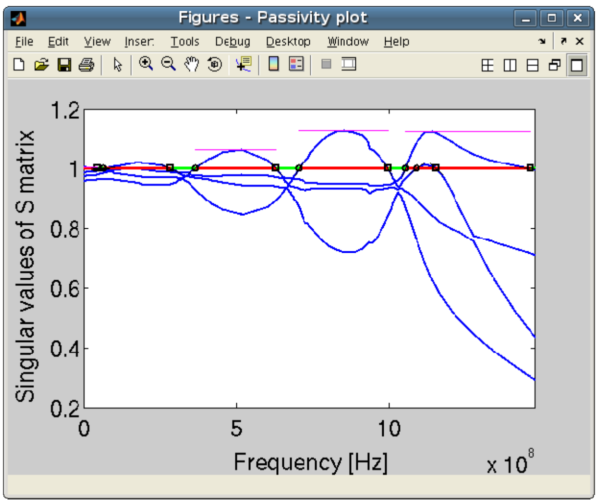
A **non passive** model, connected to **passive** loads may lead to an **unstable** circuit!

Example:



Not passive

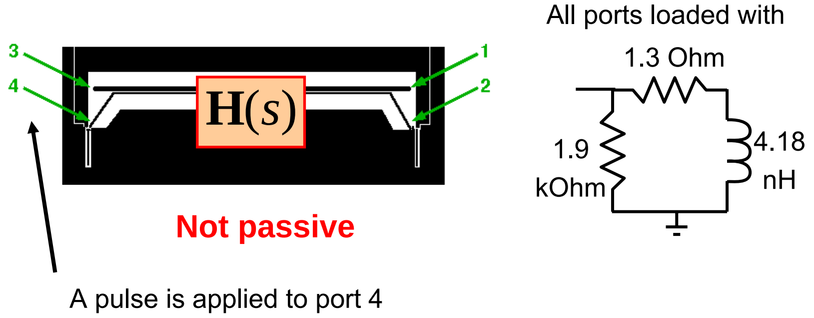
Passivity violations in MODELS: issues



Courtesy of IdemWorks s.r.l.

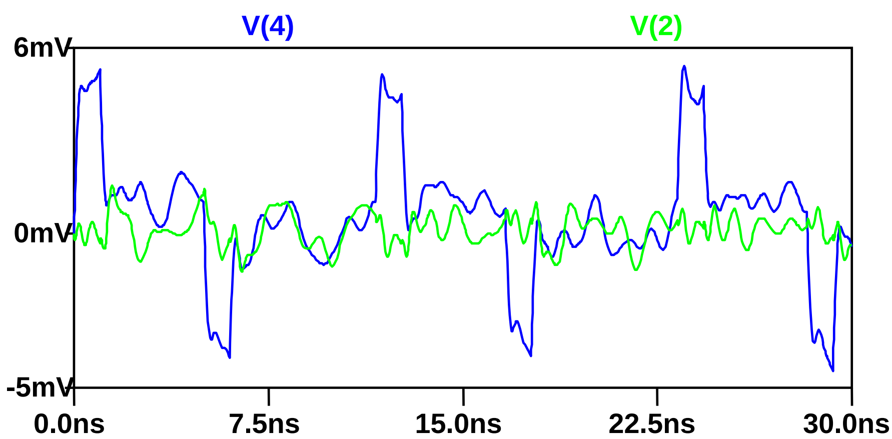
Destabilizing load

- We can always find a passive load that makes the whole system unstable!

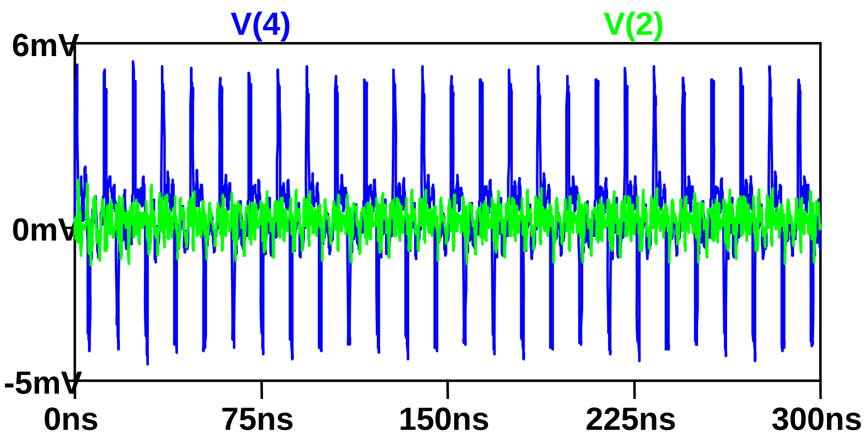


S. Grivet-Talocia, "On Driving Non-passive Macromodels to Instability" , *International Journal of Circuit Theory and Applications*, vol. 37, n. 8, pp. 863-886, October, 2009

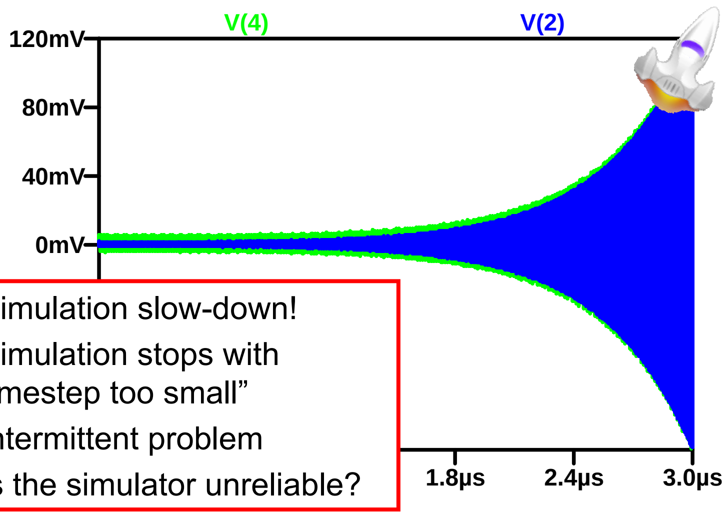
Transient simulation results



Transient simulation results

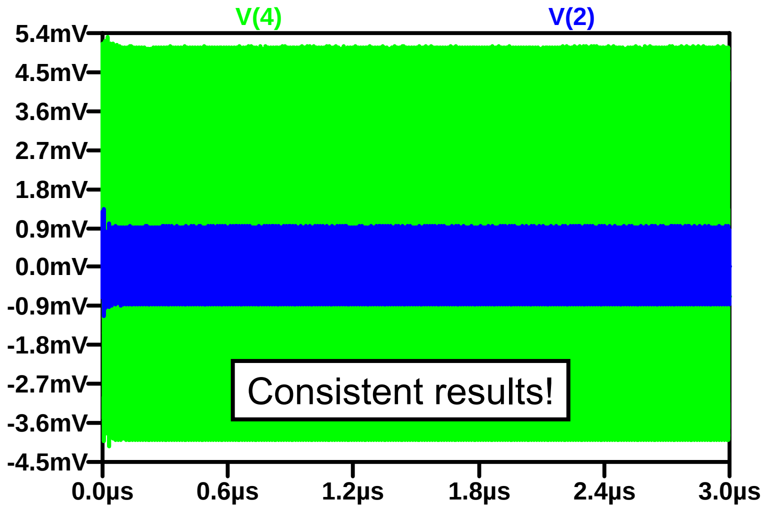


Transient simulation results



- Simulation slow-down!
- Simulation stops with “Timestep too small”
- Intermittent problem
- Is the simulator unreliable?

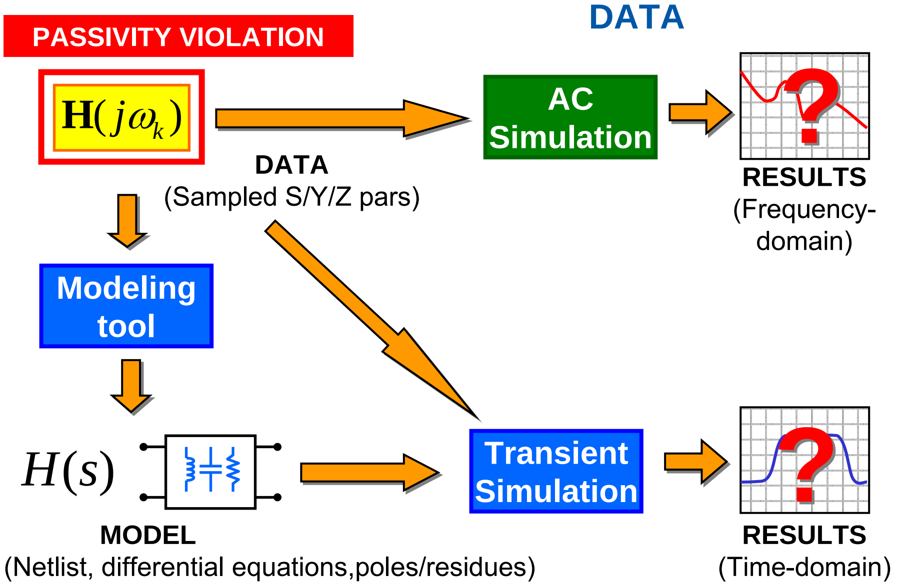
If model passivity is instead enforced...



Best practices

- Use passive models for passive components!
- If a given model violates passivity, compensate the violation with one of the well-established methods (see references at the end):
  - convex optimization
  - Hamiltonian matrices
  - linear and quadratic programming
- If violations are large, compensate violations with discretion! Or take the safe way: redo the model

Passivity violation in the DATA



Passivity in frequency domain

Passivity conditions (frequency domain):

1) $\mathbf{H}(-j\omega) = \mathbf{H}^*(j\omega)$

2) $\mathbf{H}^H(j\omega)\mathbf{H}(j\omega) \leq \mathbf{I}$

3) Check if $\mathbf{H}(j\omega)$ is causal

(i.e. check dispersion relations)

$$\boxed{\mathbf{H}(j\omega)}$$

- Mind the third condition!
- Allow for a complete passivity check for tabulated data

P. Triverio, S. Grivet-Talocia, "Robust Causality Characterization via Generalized Dispersion Relations" , *IEEE Trans. on Advanced Packaging, vol.31, n.3*, August, 2008

Passivity violations in FREQUENCY DATA

HOW can passivity violations arise?

- Numerical simulation: poor meshing, bad models or assumptions on material properties, inaccurate solver, human mistakes
- Measurement: Improper VNA calibration/de-embedding, human mistake, noise
- What happens if starting frequency data are not passive?

Example: passive vs non-passive data

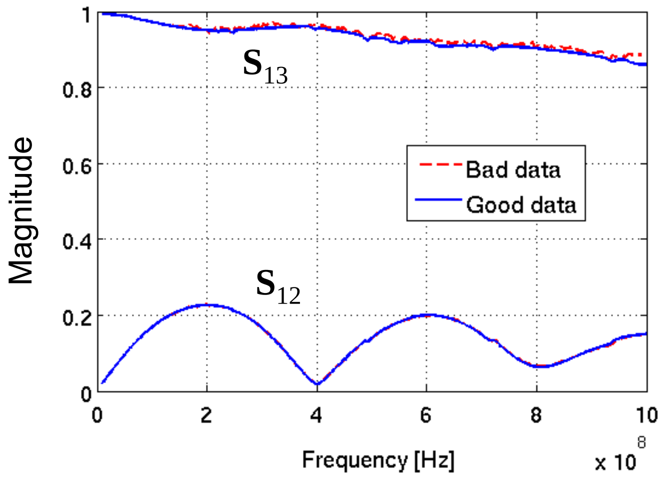
- For this PCB coupled lines, two different measurements were performed

S-parameters measured with VNA

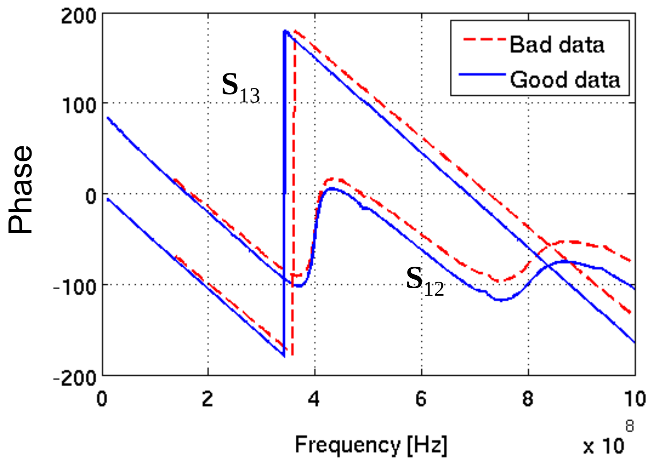
Improper calibration → **Non-passive dataset**

→ **Passive dataset**

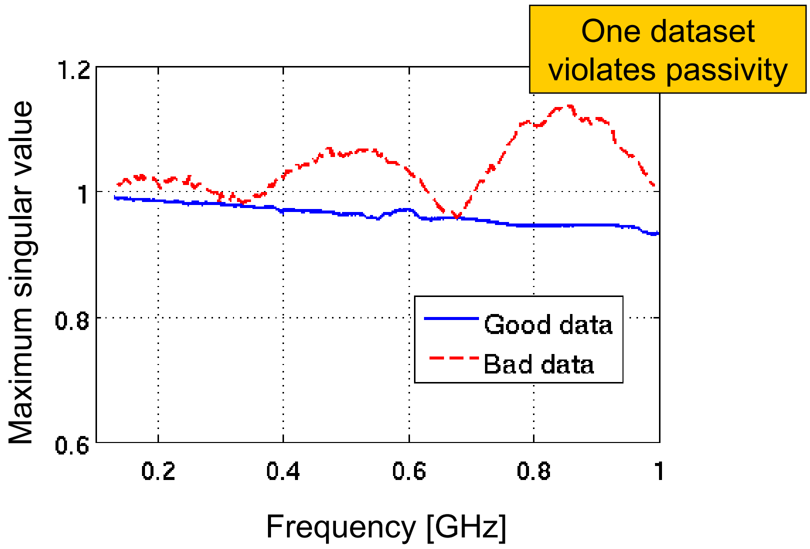
Example: passive vs non-passive data



Example: passive vs non-passive data



Example: passive vs non-passive data



Example: passive vs non-passive data

Passive data

Non-passive data

→ $\mathbf{H}(s)$ → $\mathbf{H}(s)$ → **?**

Vector Fitting

Passivity Enforcement

Example: passive vs non-passive data

Non-passive data **Passive data**

Vector Fitting model order			
6			
12			
18			

S.Grivet-Talocia and P.Triverio, SPI2010 Tutorial lecture, 9 May 2010, Hildesheim, Germany

Example: passive vs non-passive data

Non-passive data **Passive data**

Vector Fitting model order	Passivity not enforced		
6	0.280		
12	0.020		
18	0.017		

Model is not passive!

Example: passive vs non-passive data

Non-passive data | **Passive data**

Vector Fitting model order	Passivity not enforced	Passivity enforced	
6	0.280	0.23	
12	0.020	0.11	
18	0.017	0.13	

Model is not passive!

Model not accurate!

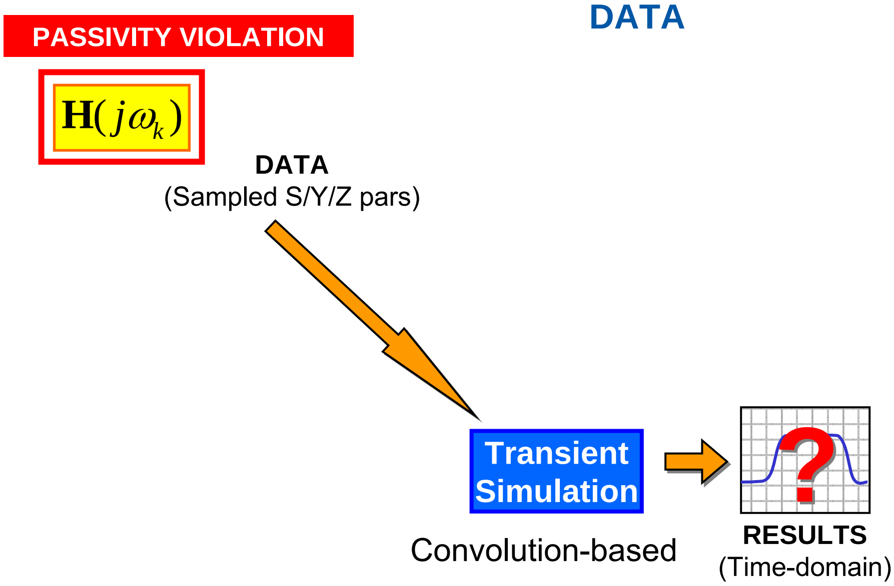
Example: passive vs non-passive data

Non-passive data | **Passive data**

Vector Fitting model order	Passivity not enforced	Passivity enforced	Passivity enforced
6	0.280	0.23	0.240
12	0.020	0.11	0.020
18	0.017	0.13	0.012

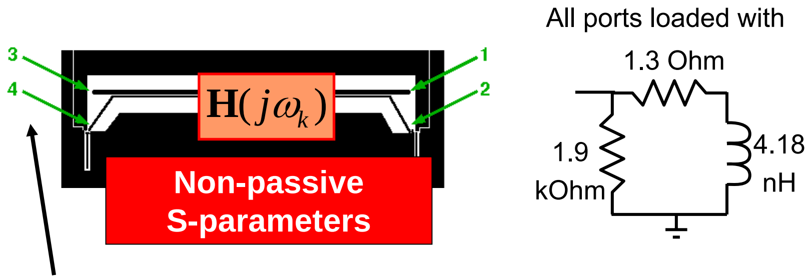
Passive & accurate!

Passivity violation in the DATA



Convolution simulation setup

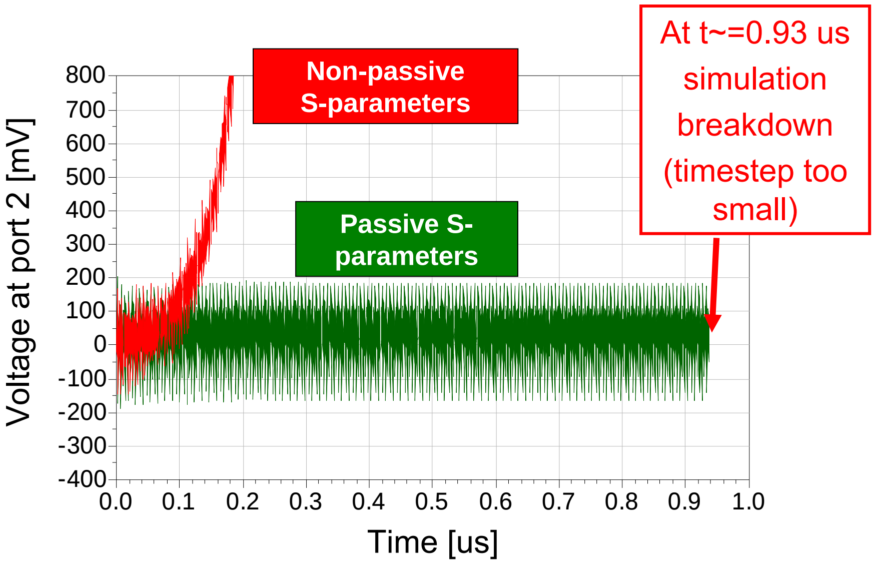
- The coupled lines (represented by the Touchstone file) are connected to a destabilizing load



A 1mA current pulse is applied to port 4

The same analysis is repeated with the **passive S-parameters**

Convolution simulation



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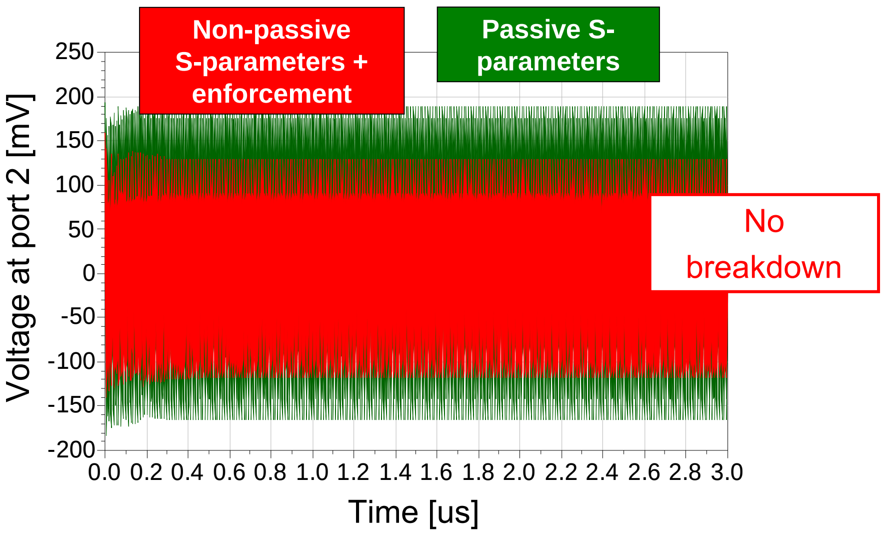
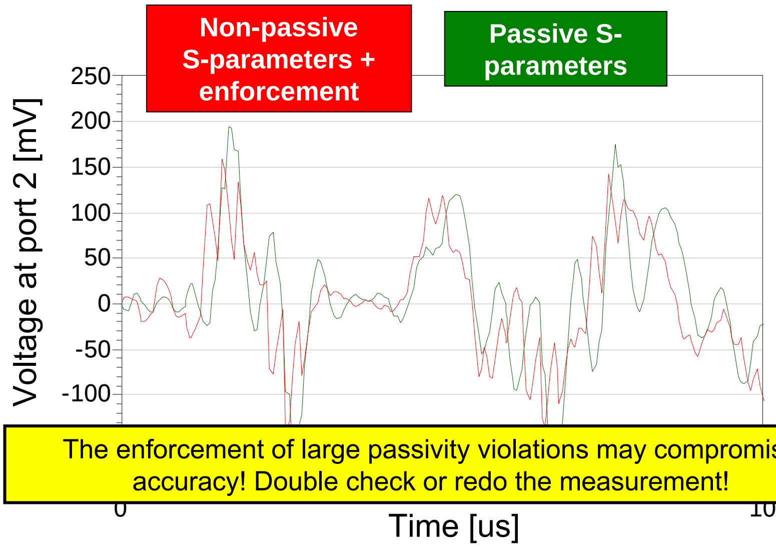
Convolution simulation (passivity enforcement ON)



Convolution simulation (passivity enforcement ON)



The enforcement of large passivity violations may compromise accuracy! Double check or redo the measurement!

Best practices

- If you have a dataset with significant passivity violations, you will have to renounce to either:
  - accuracy (will you trust your results?)
  - model passivity (simulations may diverge!)
- Promptly scan your measured/simulated data for passivity violations! For an algorithm, see [1]
- And reject “bad” datasets!

[1] P. Triverio, S. Grivet-Talocia, "Robust Causality Characterization via Generalized Dispersion Relations" , *IEEE Trans. on Advanced Packaging, vol.31, n.3*, August, 2008

Conclusion

- Comprehensive overview of **causality, stability & passivity** and their interrelations

- Impact of physical consistency violations on modeling and simulation tasks
  - models with violations → **divergent simulations**!
  - data with violations → either **inaccurate models** or **unstable simulations**

- When consistency is preserved → **Accuracy, speed and reliability** of CAD tools is maximized!

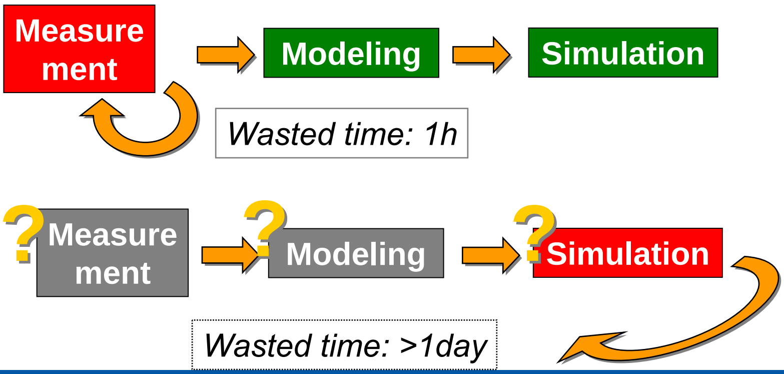
Conclusion

- Being aware of the importance of physical consistency can improve the design workflow significantly!

Measure ment → **Modeling** → **Simulation**

Conclusion

- Problems can be fixed right away!
- Physical consistency checks greatly help to identify the real source of the problems!



Thank you!

☺

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